Gravitational Radiation Recoil from Merging Black Hole Binaries

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Outline

- Introduction
- Methodology
- Results

Introduction

- Barring very special symmetries, merging massive black hole binary systems will emit gravitational waves (GWs) that are *asymmetrical*.
- Asymmetric emission of GWs can impart kick to the merger remnant due to linear momentum conservation.
- High kick velocity can unbound the merged black hole from the center of the host structure, thus can have significant *astrophysical* implications on
  - growth scenarios of massive black holes
  - growth and retention of intermediate-mass black holes in dense stellar clusters
  - effects of displacement of merged black holes on the structure of galatic nuclei.

Introduction

- Kick calculations have a long history with earlier attempts by Peres(1962); Bekenstein(1973); Fitchett(1983); Wiseman (1992).
- Recent closed-form studies include [mass ratio ρ]
  - Favata, Hughes, Holz (2004): BH Perturbation; e.g. $\rho \sim 0.127$, $v_{kick} \sim$ 20–200 km/s.
  - Blanchet, Qusailah, Will (2005): Post-Newtonian up to 2PN order; e.g. $\rho \sim 0.38$, $v_{kick} \sim$ 200–300 km/s.
  - Damour, Gopakumar (2006): PN e.g. $\rho \sim 0.38$, $v_{kick} \sim$ 74 km/s.
- Main weakness of the closed-form studies is in uncertainties of kick estimates beyond “ISCO (Innermost stable circular orbit)”.
- These results strongly indicate contributions to kick up to ISCO is very small ($\sim$ a few tens of km/s) and over 90% of the kick comes beyong ISCO to plunge/merger.

Introduction

- Therefore, accurate estimates of kicks requires full numerical relativity simulations.
- Recent numerical studies include
  - Campanelli (2005): Numerical Relativity + perturbative hybrid. ρ ~0.5, v_{kick} ~100-380 km/s.
  - Herrmann, Shoemaker, Laguna (2006): Full numerical relativity. Estimates only give lower limits and only for $\rho =$ 1.0 – 0.85. $v_{kick} \sim$ 33km/s for $\rho = 0.85$.

Methods: HAHNDOL code

- Full numerical relativity code based on a version of BSSN system of equations.
- Start with a quasi-circular initial data following the scheme similar to the one used for equal mass inspiral.
- To calculate kick, first calculate waveforms carried away by GWs during the merger.
- Use NP Weyl tensor component Ψ_4 to analyse (outgoing) gravitational wave content.
- Harmonic decomposition

$$\Psi_4(r,\theta,\phi,t) = \sum_{lm} A_{lm}(r,t)\,{}_{-2}Y_{lm}(\theta,\phi)$$

$$A_{lm}(r,t) = \int \Psi_4(r,\theta,\phi,t)\,{}_{-2}Y_{lm}(\theta,\phi)\,d\Omega$$

Hahndol code

- Given Ψ_4, one can calculate, e.g., E, P_i.

$$E_{GW} = \frac{r^2}{4\pi}\int\int_\Omega |\int_{-\infty}^t dt'\Psi_4(t',r,\theta,\phi)|^2 d\Omega dt$$

$$P^i_{GW} = \frac{r^2}{4\pi}\int\int_\Omega \frac{x^i}{r}|\int_{-\infty}^t dt'\Psi_4(t',r,\theta,\phi)|^2 d\Omega dt$$

- $M_{merged}V_{kick} + P_{GW} = P_{init}$. We choose $P_{init} = 0$ in our initial data.

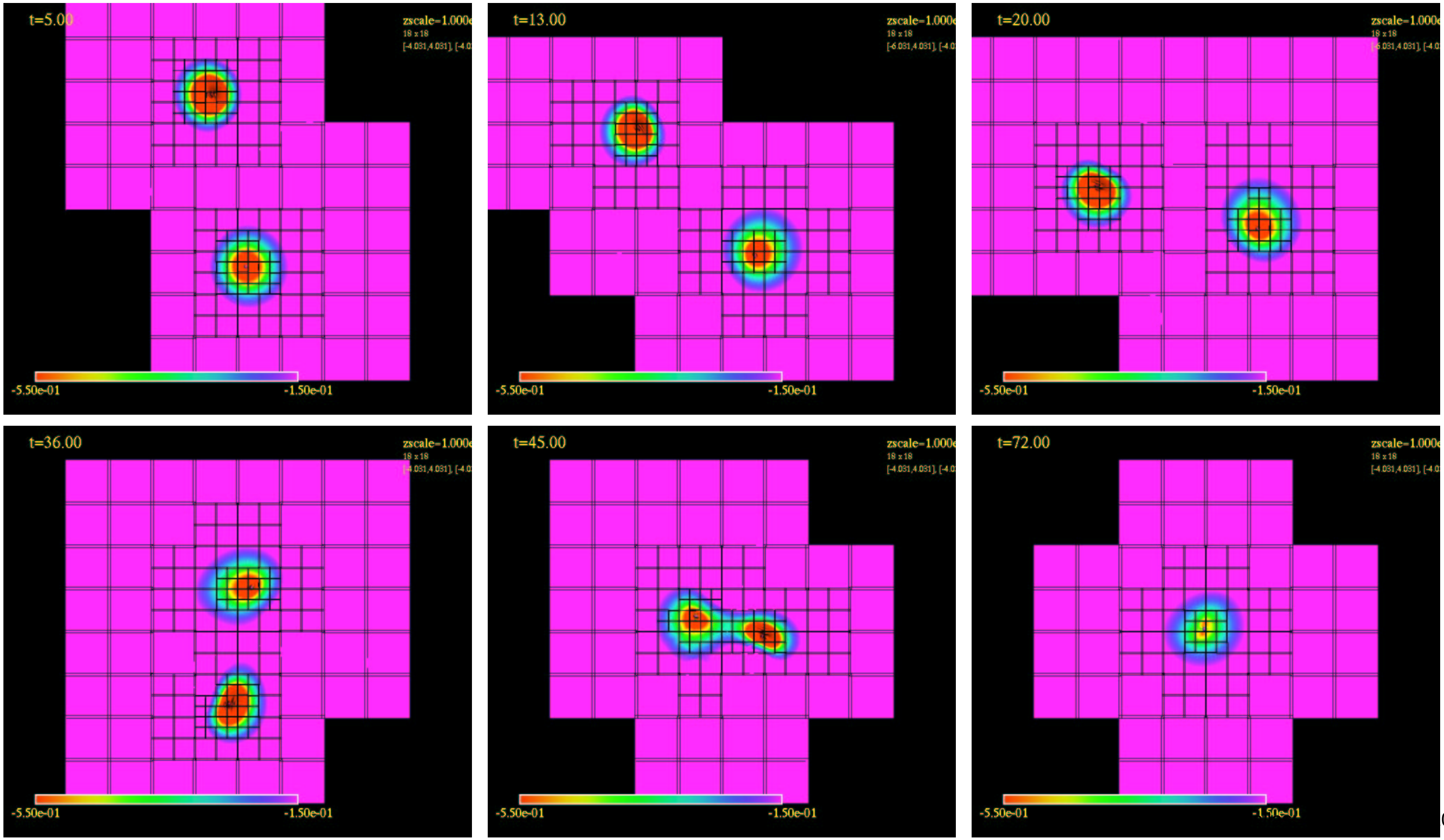
Results

- Start with NON-spinning cases.
- Mass ratio $\rho = M_1/M_2 = 0.667(, 0.5)$.
- Harmonic mode analysis of waveforms indicates that dominant contribution comes from $L = 2, M = 2$ and $L = 3, M = 3$ mixing.
- Initial data: $L/M = 4.1M, 6.2M$ with M total (initial) ADM mass.
- Resolutions used: $h_f = M/32, M/40, M/48$

- Solution
- Gravitational waveforms
- Kick estimates

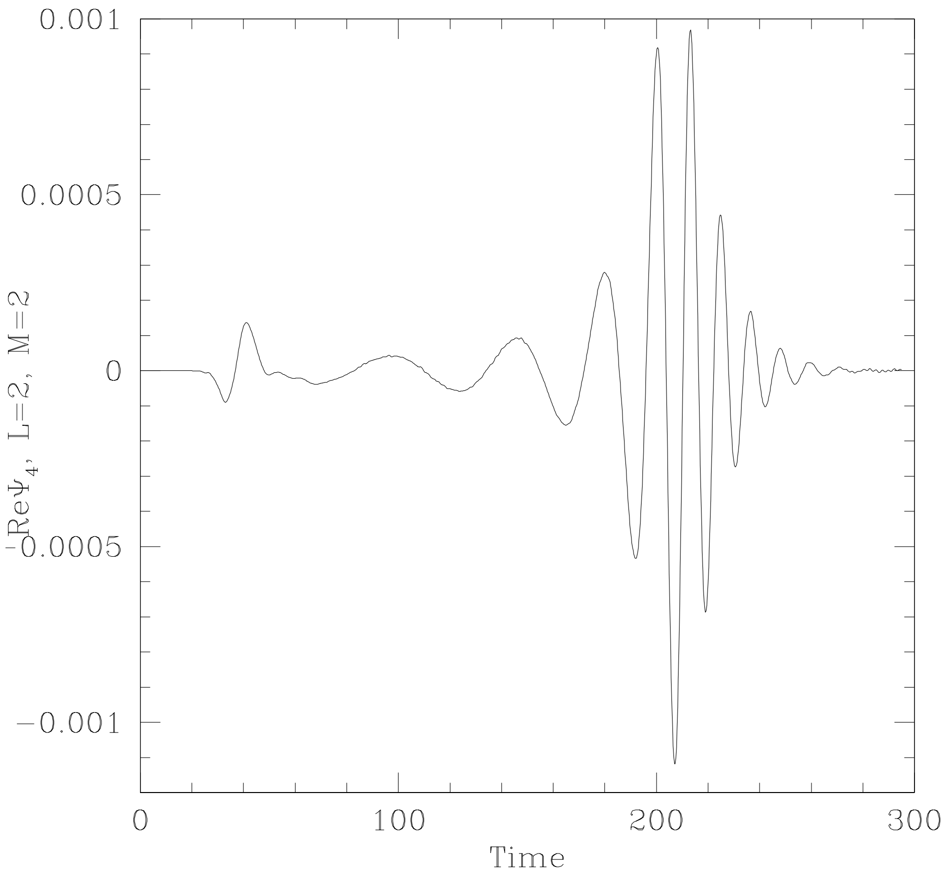
Results: Solution

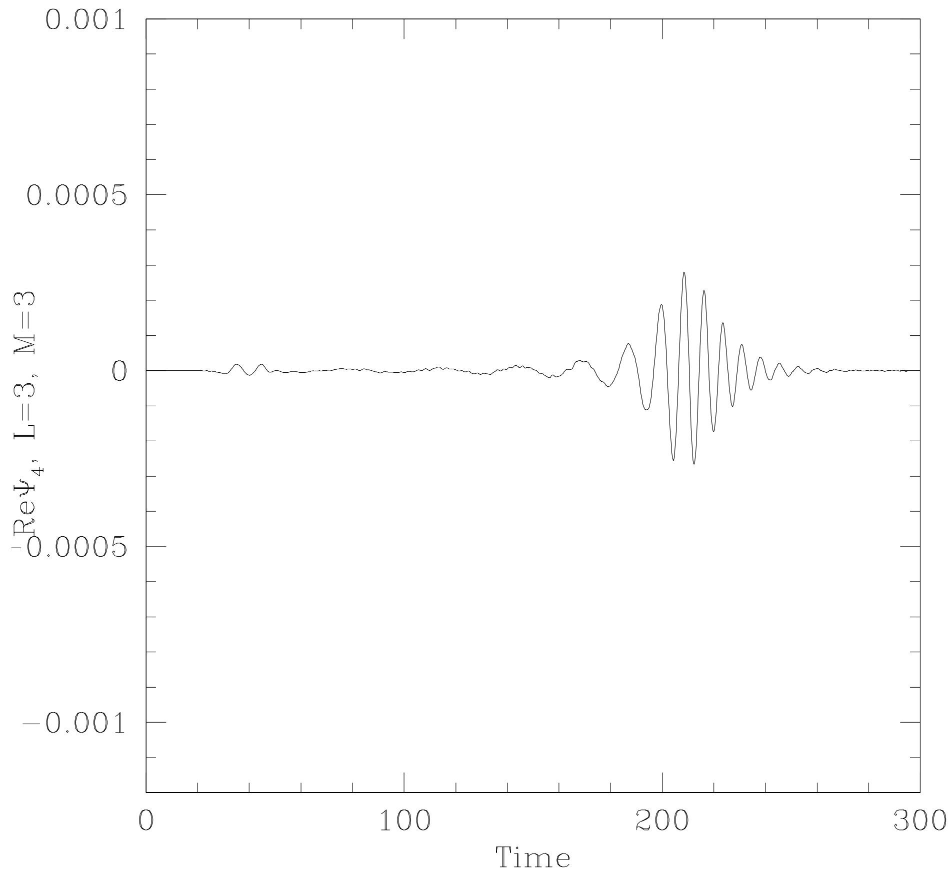
- Snapshots of grid structure: Re(χ) ($\chi =$ Coulomb scalar) on $z = 0$ plane at $t = 5M, 13M, 20M, 36M, 45M, 72M$ [MOVIE]



Results: Gravitational Waveforms

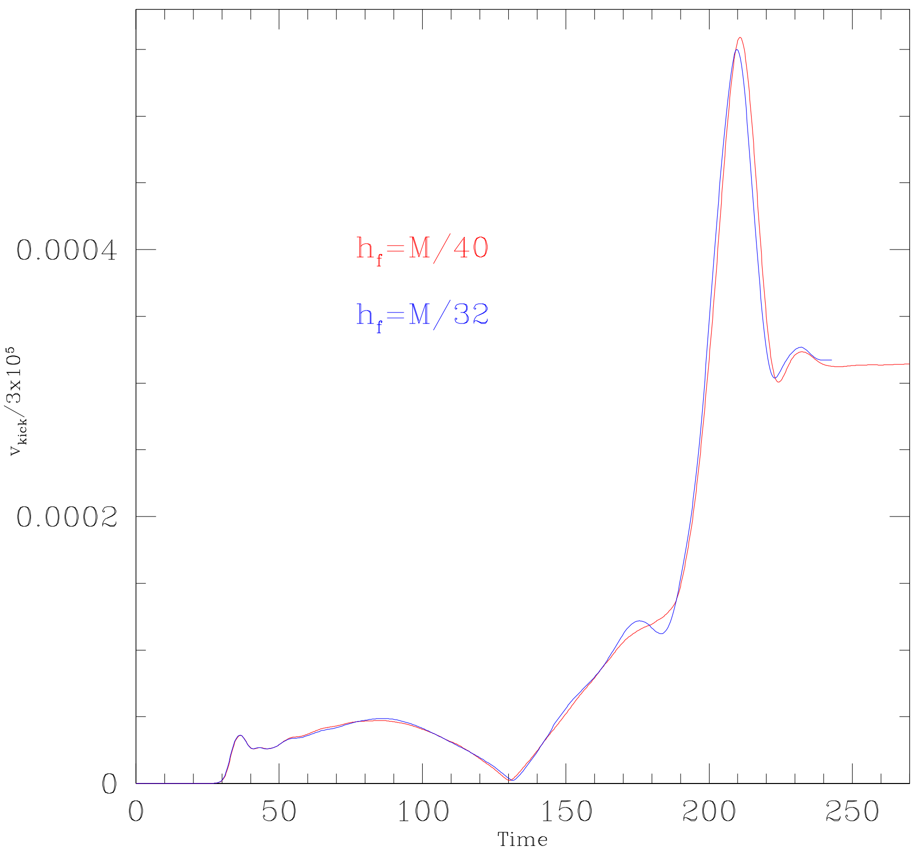
$\Psi_4(L = 2, M = 2 \;\&\; L = 3, M = 3)$
$\rho = 0.667, d_{init}/M \sim 6.2, h_f = M/40$





Results: kick estimates for $\rho = 0.667$

- $\rho = 0.667, d_{init}/M = 6.2$
- $h_f = M/32, M/40$ (different gauge conditions used.)



Results: Kick estimates for $\rho = 0.667$

- "kick" $= v(t) = \frac{1}{M}\sqrt{\left(\int^t \frac{dP_x(t')}{dt'}dt'\right)^2 + \left(\int^t \frac{dP_y(t')}{dt'}dt'\right)^2}$
- Kick velocity ~ 105km/s$\pm 10\%$.

(Time-shifted so that the pick of amplitude of waveforms match.)